'iolation of scaling in hadronic interactions at ltrahigh energies

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It is concluded on the basis of an analysis of experimental data on EAS that scale invariance is violated in hadron interactions in the energy region 10^{15}–10^{17} eV; the character of these violations is analyzed.

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We present here an analysis of the aggregate of experimental data on EAS in ›nnection with the question of scaling violation in hadron interactions. The in- usive spectra of the secondary particles produced in interactions of nucleons .d pions with nucleons have been well established during the last few years, and this makes it possible to calculate with good accuracy the different characteristics of EAS and to compare the calculation results with experiment.

The most thoroughly investigated by now are the electron and muon components of EAS, and it is precisely in these EAS components that it is necessary to verify primarily the possibility of extrapolating the scaling model from the accelerator-energy region to the region of ultrahigh energies 10^{15}—10^{17} eV [1,2]

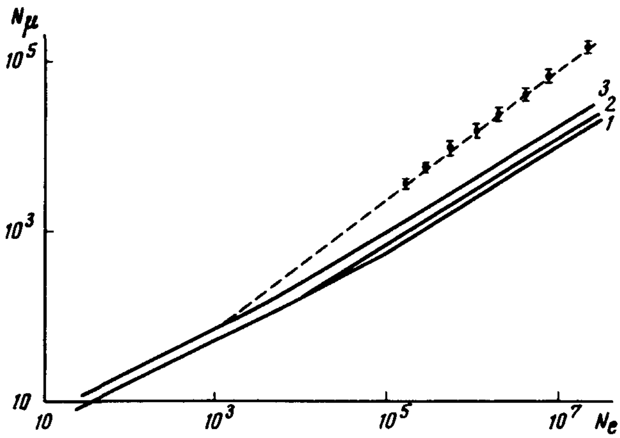

FIG. 1. Dependence of the number of muons with energy > 10 GeV on N_e; ● — data of[3]; curve 1—constant cross sections corresponding to ranges 80—120 g/cm^2 for nucleons and pions respectively, curves 2 and 3—cross sections increase 10% when the energy increases by one order of magnitude; curves 1 and 2—the inclusive spectra correspond to[2], curve 3—multiplicity increased 1.5 times on account of small x.

Figure 1 shows the dependence of the number of muons N_μ with energy > 10 GeV on the number of electrons N_e in EAS generated by primary protons. The $N_\mu(N_e)$ dependence was calculated under various assumptions concerning the interaction cross section and the form of the structure functions. Calculation shows that the scale-invariance model, even with allowance for rather appreciable variations of the characteristics of the elementary act, is in strong contradiction with both the absolute of N_μ and the character of the $N_\mu \sim N_e^\alpha$ dependence ($\alpha = 0.60$ according to calculation, whereas experiment yields $\alpha = 0.78 \pm 0.01$). From a comparison of the calculation results with an extrapolation of the experimental data into the region of small N_e and N_μ it follows that the deviations from scaling should begin at energies that are higher by approximately one order of magnitude than accelerator energies, and become appreciable at 10^{14}—10^{15} eV. It is still impossible to draw from these data any definite conclusion concerning violation of scaling in the region of ultrahigh energies, inasmuch as the primary radiation can contain heavy nuclei, allowance for which can lead to an increase in the ratio N_μ/N_e and decrease somewhat the discrepancy with experiment. Calculations show that this possibility cannot be fully excluded on the basis of the existence of large fluctuations in the number of muons at a fixed number of electrons (or vice versa), although for an increase in the ratio N_μ/N_e to exist simultaneously with fluctuations of the

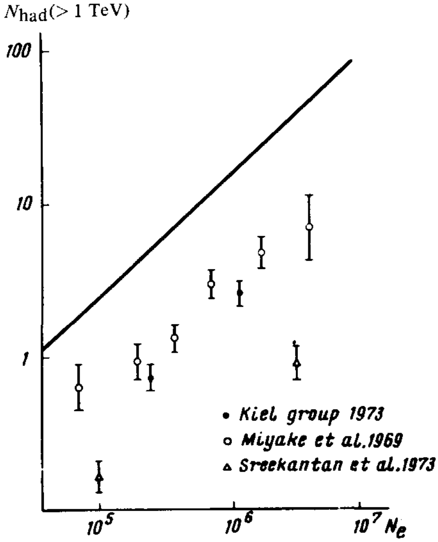

FIG. 2. Dependence of the number of hadrons with energy >1 TeV on N_e at mountain altitude: solid line—calculation by scaling model; the experimental data are taken from.[4]

ecessary magnitude it is necessary to assume an extremely exotic composi-ion of the primary radiation, in which nuclei heavier than those of iron redominate.

However, our calculations have shown that an appreciable discrepancy be-ween the scaling model and experiment is observed also in the analysis of the xperimental data on the hadron component of EAS under the assumption that he primary particles are protons (see Fig. 2). The theoretical dependence of he number N_H of hadrons with energy >1 TeV on $N_e(N_H \sim N_e^{\alpha})$ is characterized y an exponent $\alpha = 0.95 \pm 0.03$ (α decreases for lower energies). It is important

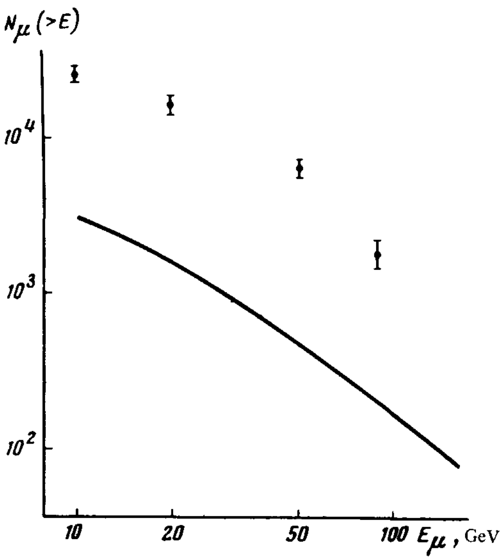

FIG. 3. Energy spectrum of muons in EAS at $N_e = 10^6$: curve—calculation by scaling model, points—data of[7].

to note two circumstances: first, the discrepancy between the scaling model and experiment has opposite signs for muons and hadrons; second, the model dependences of both $N_\mu(N_e)$ and $N_H(N_e)$ are characterized by an exponent $\alpha < 1$. At the same time, the entire aggregate of the experimental data of the interaction of nucleon-nucleus and nucleus-nucleus interactions, obtained both in cosmic rays and with accelerators, offer evidence of an extremely small role (< 1%) of collective effects in these interactions. Therefore the interaction of nuclei of primary radiation reduces in fact to their consecutive fragmentation. In this case, according to[5], the dependence of any characteristic of EAS at a given N_e on the mass number of the nuclei is proportional to $A^{1-\alpha}$, if this characteristic depends on N_e like N_e^α for the primary proton.

Thus, while the introduction of heavy nuclei into the primary radiation can decrease the discrepancy between experiment and calculation for muons, on account of the increase of the number of muons in the shower with a given number of electrons, it leads at the same time to an increase of the discrepancy for hadrons, since the number of the latter also increases (we recall that $\alpha < 1$ for both hadrons and muons). This argument is decisive in the sense of excluding the influence of arbitrary assumptions concerning the chemical composition of the primary radiation on the reliability of the conclusion concerning violation of scaling.

Let us see now how the model of hadron interactions must be changed in the region of ultrahigh energies in comparison with the model obtained from research with accelerators.

It is known that at accelerator energies scaling is satisfied, even in the fragmentation region, only for pions, and in principle the role of heavier particles can increase with energy. Since the experimental data pertain to muons of relatively low energy, it is meaningless to make distinctions between secondary pions and kaons. The role of $N\bar{N}$ pairs was investigated in[6], where it was shown that although the increase of the fraction of $N\bar{N}$ pairs among the secondary particles from 5 to 40% increases appreciably (by two or three times) the fraction of muons of low (< 10 GeV) energy, the fraction of muons of energy > 50 GeV changes insignificantly. At the same time, as seen from Fig. 3, where the experimental data are given on the energy spectrum of the muons in EAS,[7] the scaling model is contradicted up to the highest muon energies (~ 100 GeV) investigated with the aid of a magnetic spectrometer. Discrepancy between calculation and experiment cannot be elimated by assuming that the cross section for the generation of $N\bar{N}$ pairs (and also of hyperons) increases.

The energy at which a strong deviation from the scaling model should take place corresponds to the energy of the unitary limit of the theory of weak interactions (10^{14}—10^{15} eV), and in this connection we can consider such exotic possibilities as, for example, violation of charge invariance or direct generation of leptons. An increase of the fraction of the π^0 mesons above the usual value ($f_{\pi^0} = \frac{1}{2}(f_{\pi^+} + f_{\pi^-})$) can lead to agreement with respect to the hadron component of the EAS, but at the same time the discrepancy with respect to muons is increased. This possibility is therefore excluded. The assumption that the leptons are directly generated can improve the agreement with the hadron component, but to obtain agreement with respect to the fraction of muons it must be assumed that a very large number of muons (on the order of 10^3 at 10^{14}—10^{15} eV) is generated in individual hadron interaction acts.

One of the best founded possibilities is apparently to assume that in the re-ion of ultrahigh energies a principal change takes place in the form of the in-lusive spectrum and in the multiplicity of the secondary particles.[8] Future xperiments, and also a future analysis of the already available data will permit choice between the various possibilities of scaling violation.

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